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Investigation on Contact Point Displacement on Driven Tyres

To make multi-body simulation for agricultural vehicle development possible with meaningful input, simple, but sufficiently accurate partial models are needed. The tyre model is essential for vehicle simulation. Knowledge about the forces arising and straining point position is necessary to design a realistic model. In this article the longitudinal displacement of the driving and contact force straining point for a tyre driven on asphalt is examined.

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Dedicated to Prof. Dr. Ing. Dr. h.c. H. D. Kutzbach on occasion of his 65th anniversary.

Keywords

Tyre, longitudinal force, tyre model, multi-body simulation

Concerning the ride characteristics of tractor tyres, in a former article the influence of lateral forces on the displacement of the straining points of the resulting forces in the contact patch for the free rolling tyre was introduced. Continuing this project it is necessary to have a look on the straining point in the longitudinal direction of the tyre. For the setup of a realistic dynamic tyre model it is necessary to investigate the influence of vertical and longitudinal forces generated by driving or braking forces. Therefore, in this article investigations and results concerning this problem are explained. To be examined is the driven/braked tyre on an asphalt driving surface without interaction of lateral forces.

Contact point of vertical force

Forces and moments of a driven or braked wheel without slip angle and the straining points are shown in *Figure 1*.

In the tyre-driving-surface contact area the exact straining point of the vertical load F_z can be determined by the torque equilibrium around the y-axis. Therefore:

$$e = \frac{M_y - F_x \cdot r_t - J_{yy} \cdot \dot{\omega}}{F_z} \qquad (1)$$

J_{yy} characterizes the moment of inertia of the tyre with the rim.

The lever arm of the tyre load herein is e. Plesser points out that in case of a driven/braked wheel the distance e is not only dependent on the rolling resistance [2]. Therefore in the following the definition „lever arm of tyre load“ proposed by Barrelmeyer is used [3]. With increasing driving moment the lever arm of tyre load is growing in driving direction. In case of the braked wheel with sufficient big tyre load F_z and high braking torques ($M_y < 0$) the amount of the lever arm of tyre load can become negative, which means the straining point moves behind the axle related to the driving direction.

In *Figure 2* the lever arm of tyre load is shown as a function of the driving torque M_t. $M_t = 0$ is the case of the free rolling tyre and the lever arm is about 9 mm. This amount characterizes the rolling resistance of the

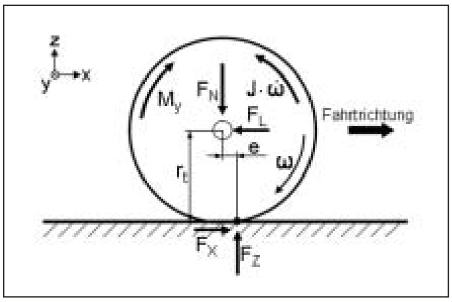


Fig. 1: Forces and torques for an agricultural tyre and their corresponding lever arms r and e

tyre. As the presented results refer to a rigid surface, it is only the internal rolling resistance (deflection of the tyre). The external rolling resistance (deformation of the ground) is not relevant for the shown conditions.

It is proposed to assume the internal rolling resistance as constant for the three operating modes „braked“, „free rolling“ and „driven“. Consequently, the lever arm of tyre load can be divided into a constant part caused by the rolling resistance and variable part caused by the interacting longitudinal force. The variable part for the driven/braked wheel is regarded as longitudinal displacement f_x, that had been investigated by Plesser. This implies that the displacement of the straining point is equivalent to the deformation of the outer contour of the tyre. Giving consideration to the results shown in *Figure 2* and the experiences gained by the authors this assumption seems to be valid for the first approach. For the torque equilibrium this results in:

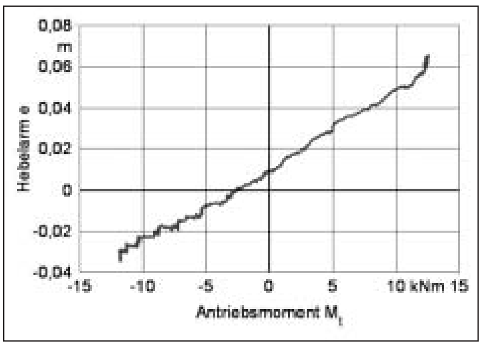


Fig. 2: Lever arm of the tyre load e depending on drive torque on a 520/70 R 34 tyre and 0.8 bar air pressure

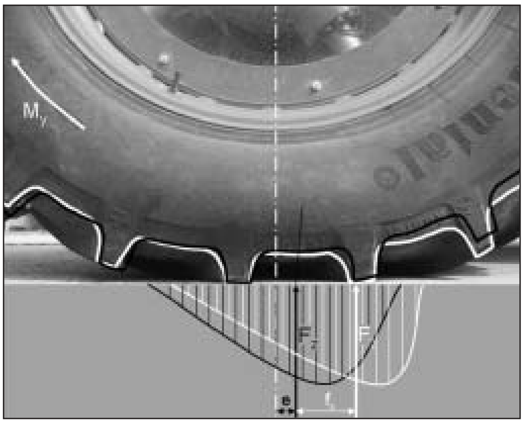
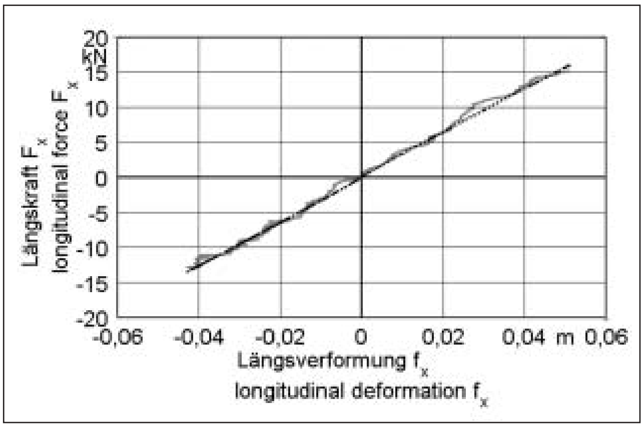


Fig. 3: Picture of a tractor tyre deformed by longitudinal force with qualitatively displayed pressure distribution. The black contour denotes the free rolling wheel.

Fig. 4: Lateral displacement F_x as a function of the slip angle for different tyre loads (Tyre: 520/70 R34, p_i = 0.8 bar, v=5km/h, asphalt)



$$M_y = F_x \cdot r_t + F_z \cdot (e + f_x) + J_{yy} \cdot \dot{\omega} \qquad (2)$$

For exemplification *Figure 3* shows qualitatively the pressure distribution within the tread area in longitudinal direction for a free rolling (black) and a driven wheel (white). Furthermore, the resulting force F_z is drawn in. It is obvious that the complete lever arm the force F_z is acting on increases with the distance f_x. From the highlighted lug contour, a displacement of the contact area can be detected clearly.

With this approach the measurement of forces and moments allows the determination of a longitudinal deformation and, therefore, a correlation of the force-distance-relation. Thus, a determination of longitudinal dynamic parameters is possible. Plesser proposes the following approach for the dynamic behaviour in longitudinal direction in the form of non-linear spring characteristics with a speed dependent digressive damping.

$$F_x = c_{1x} \cdot f_x^{c_{2x}} + (d_{1x} \cdot \frac{1}{v^{d_{2x}}}) \cdot \dot{f}_x \qquad (3)$$

While c_{1x} describes the spring stiffness of the tyre, c_{2x} affects the progression of the spring characteristic curve. The damping constant d_{1x} is extended by a speed dependent part d_{2x}. A detailed description of the model is given in [2]. Inserting in equation 2 results in:

$$M_y = \left(c_{1x} \cdot f_x^{c_{2x}} + (d_{1x} \cdot \frac{1}{v^{d_{2x}}}) \cdot \dot{f}_x \right) \cdot r_t + F_z \cdot (e + f_x) + J_{yy} \cdot \dot{\omega} \qquad (4)$$

For steady state operating mode (f_x = const) the speed dependent damping becomes zero.

Investigation methods

Using the Hohenheim single wheel tester, which has been the basis of several research projects, the tractive or braking force F_x, lateral force F_y, and vertical force F_z, along with the inclination torque M_x, driving or braking torque M_y, and the aligning torque M_z can all be determined by means of a six-component hub gauge. Furthermore, the distance between wheel centre and ground, as well as the real and the theoretical speed is recorded. At controlled tyre load the measuring wheel can be driven respectively braked by a hydraulic motor [3].

So it is possible to measure all parameters in equation 4. Furthermore, the Single Wheel Tester provides the opportunity to examine longitudinal and vertical behaviour of the tyre independent from each other. Inflation pressure, tyre load and driving speed can be varied.

For the determination of the internal rolling resistance e tests with free rolling tyre are started at first. The measuring wheel is decoupled from the drive. For further parameterization quasi-steady-state tests are performed, that means the variation of the slip is realized by selecting a long acceleration time t_B = 20 s, which is the period from the blocked wheel up to the turning wheel at maximum speed. According to equation 3 the longitudinal deflection speed is very small on these conditions, so the damping part with the small tyre damping can be ignored. Also the part caused by inertia can be neglected at slow slip variation. So the two spring parameters c_{x1} and c_{x2} are the only unknown in equation 4, all other parameters are being measured. By means of the approach in equation 3 the two parameters can be determined by adapting to the measured curve. *Figure 5* shows the fitted curve (dotted, dark) above the measured (bright).

Due to the variation of the results, 3 tests for each setup were performed, that were averaged. For the measured tyre of the size 520/70 R34 on the conditions shown in *Figure 5* this takes to:

- e = 0,0085 m
- c_{1x} = 274 kN/m
- c_{2x} = 0,96

It comes out a calculated displacement f_x, which increases nearly linearly with the longitudinal force F_x under these conditions. Comparing with the results of Plesser shows that the progression differs a lot from the displayed results. Whereas Plesser determined a range between 1.4 and 1.5 for c_{2x}, the progression shown above can nearly be ignored. If the non-linear tyre behaviour is linearized, that means an approximation for c_{2x} = 1 with Plesser's results, the achieved results are comparable. On these conditions Plesser determined the following values:

- c_{1x} = 700 kN/m
- c_{2x} = 1,4

After the approximation for c_{2x} = 1 c_{1x} becomes about 250 kN/m.

Therefore, the new method is recommended for the determination of longitudinal dynamic parameters especially for the application in vehicle dynamics simulation. A linearization seems to be reasonable especially for small deformations and longitudinal forces without falsifying the particularization improved by the non-linear tyre model substantially.

Outlook

First tests with a corresponding tyre model are promising and are explained in a further article. For the validation of the assumption that the geometric longitudinal displacement f_x is equivalent to the relocation of the straining point further examinations of the influence of acceleration time, tyre load, inflation pressure and driving speed will be performed. Furthermore, the possibility for a determination of the damping parameters will be investigated by reducing the acceleration time.

Literature

Books are identified by •

[1] *Schreiber, M., C. Brinkmann und V. Schlotter*: Untersuchungen zum Angriffspunkt der resultierenden Kräfte im Reifenlatsch. Landtechnik 58 (2003), H. 5, S. 298-299

[2] • *Plesser, J.*: Dynamisches Verhalten von Ackerschlepperreifen in Vertikal- und Längsrichtung auf fester Fahrbahn. Dissertation, Universität Stuttgart, 1997; VDI-Verlag, Düsseldorf, Reihe 14, Nr. 83

[3] • *Barrelmeyer, Th.*: Untersuchung der Kräfte an gelenkten und angetriebenen Ackerschlepperrädern bei Gelände- und Straßenfahrt. Dissertation, Universität Stuttgart, 1996; VDI Verlag, Düsseldorf, Reihe 14, Nr. 79